

Influence of scattering on ballistic nanotransistor design

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Importance of this work: (i) This is the first work to model electron-phonon scattering within a quantum mechanical approach to nanotransistors. The simulations use the non equilibrium Green's function method. (ii) A simple equation which captures the importance of scattering as a function of the spatial location from source to drain is presented. This equation helps interpret the numerical simulations. (iii) We show that the resistance per unit length in the source side is much larger than in the drain side. Thus making scattering in the source side of the device much more important than scattering in the drain side. Numerical estimates of ballisticity for 10nm channel length devices in the presence of electron-phonon scattering are given. Based on these calculations, we propose that to achieve a larger on-current in nanotransistors, it is crucial to keep the highly doped source extension region extremely small, even if this is at the cost of making the highly doped drain extension region longer.

Device The device in the inset of Fig. 1 shows the Dual Gate MOSFET (DG MOSFET) considered. The channel (hatched) length is 10 nm, and l_{Ex-s} and l_{Ex-d} are the highly doped regions. The thickness of the channel is 2 nm, the gate length is 10nm and the oxide thickness is 1 nm.

New Results:

Simple Argument: The electrostatic potential through a typical DG MOSFET is shown in Fig. 2. After a scattering event, the kinetic energy of an electron in the transport direction falls into two distinct regimes: larger or smaller than the source injection barrier (E_b). The probability of these are represented by $P(E_t^+ < E_b)$ and $P(E_t^+ > E_b)$, where E_t is the energy component in the plane of the MOSFET shown in Fig. 1, and + (-) denotes the electrons traveling towards the drain (source). In Ex-s, all electrons with $E_t^+ < E_b$ and any E_t^- are reflected to the source and so do not contribute to current. In the Ch and Ex-d regions, all electrons that have $E_t^- < E_b$ and any E_t^+ are transmitted to the drain after a scattering event, and so contribute to current. The above thoughts can be used to define a measure of the forward scattering probability (F), which is the probability for an electron to reach the drain after a scattering event at y (Ex-s, Ch and Ex-d regions),

$$\begin{aligned} F(y < y_b, E) &= P(E_t^+ > E_b) \\ F(y > y_b, E) &= P(E_t^+ > E_b) + P(E_t^- < E_b), \end{aligned}$$

where, y is the source-drain direction and y_b is the location of the source injection barrier (E_b), E is the total energy, and $P(E_t^- < E_b) + P(E_t^+ > E_b) = 1$. It is important to note that a scattering event in the Channel and Ex-d can contribute to current with a higher probability than scattering in the source due to the $P(E_t^- < E_b)$ term above. If we now restrict ourselves to elastic phonon scattering,

$$\begin{aligned} F(y < y_b, E) &= \frac{1}{2\pi} \arccos \left[2 \frac{E_b - V_y}{E - V_y} - 1 \right] \\ F(y > y_b, E) &= 1 - \frac{1}{2\pi} \arccos \left[2 \frac{E_b - V_y}{E - V_y} - 1 \right], \end{aligned}$$

where, V_y is effective potential at location y .

The above equations give a wealth of qualitative information as shown in Fig. 2, which is a plot of F versus y : (a) F is small to the left of the source injection barrier. (b) F increases with y to the right of the source injection barrier as the density of states below the source injection barrier aids current flow. (c) The higher energy electron is more ballistic to the left of the source injection barrier and less ballistic to the right of the source injection barrier. (d) Comparing the data for the two different drain voltages, we immediately see that F to the right of the source injection barrier is smaller for a smaller applied voltage. Experiments also show a smaller ballisticity at smaller drain voltages.

Rigorous Calculations: It is useful to define the following figures of merit $b(E)$ (ballisticity at total energy E) and B (total ballisticity),

$$\begin{aligned} b(E) &= \frac{\text{Scattering on-current at } E}{\text{Ballistic on-current at } E} \\ B &= \frac{\text{Total scattering on-current}}{\text{Total ballistic on-current}}. \end{aligned}$$

To demonstrate the role of scattering in different regions, we first consider an example where scattering is present only in Ex-s and Ex-d respectively. Fig. 3 shows the current distribution versus energy E_t for an electron. The ballistic current distribution (solid curve) does not depend on the location of the cross section and is non zero only when E_t is larger than the conduction band at the source end. Scattering only in Ex-s results in a current distribution over an energy window that is very similar to the ballistic case, though, diminished in magnitude due to reflection (dashed). In sharp contrast, scattering only in Ex-d has a large tail for E_t smaller than the conduction band at the source end (dash-dot). As a result of this tail, on-current diminishes by a significantly smaller amount due to scattering in Ex-d rather than scattering in Ex-s. Fig. 3 also justifies the simple arguments that led to Fig. 2. The total ballisticity (B) when scattering is present only in Ex-d (96%) is much larger than when scattering is present only in Ex-s (64%).

We now present results with scattering included in the entire device (Ex-s, Ex-d and Ch). Fig. 4 shows the ballisticity $b(E)$ for three devices with different values of source and drain extension regions (l_{Ex-s}, l_{Ex-d}). The devices are otherwise identical and have identical ballistic on-currents. The important point to note in this figure is that the ballisticity is largest for the (l_{Ex-s}, l_{Ex-d})=(3nm,9nm) device. The total ballisticity B of the (3nm,9nm) and (9nm,3nm) devices are 67.2% and 52.6% respectively, meaning that the on-current of the former device is almost 28% larger. $b(E)$ of a (6nm,6nm) device lies in between the other two devices in agreement with the qualitative discussion. The gate and drain voltage for the data shown in Fig. 4 are 1.3 V and 1 V respectively. Note also that the computed B of the (3nm,9nm) device at a drain voltage of 0.1V is 10% smaller than at 1V. This follows because the fraction of density of states in / near the drain extension region available for scattering below the source injection barrier is smaller at smaller drain voltages. Finally, $b(E)$ is on an average larger at smaller energies.

We find that scattering in the source extension region is the most deleterious to the on-current of nanotransistors, more deleterious than scattering in the channel or the drain extension region. Detailed simulations to prove this point and a simple intuitive picture are presented. Numerical estimates for ballisticity are given. These extension regions will only be of the order of one or a few mean free paths in nanotransistors. Hence, the

use of mobility may not be an appropriate quantity in short extension regions. So the influence of electron-phonon scattering in diminishing the ballisticity is modeled using the non equilibrium Green's function approach.

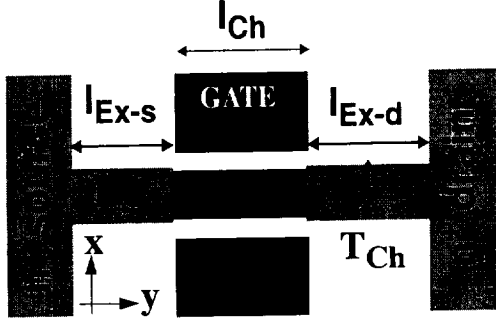


Fig. 1. Schematic of a Dual Gate MOSFET (DG MOSFET) simulated. The doping in Ex-s and Ex-d regions need not be the same as that in the source and drain. The hatched region is the channel. The white region between the source / drain / channel and the gate is oxide. The direction normal to the page is infinite in extent.

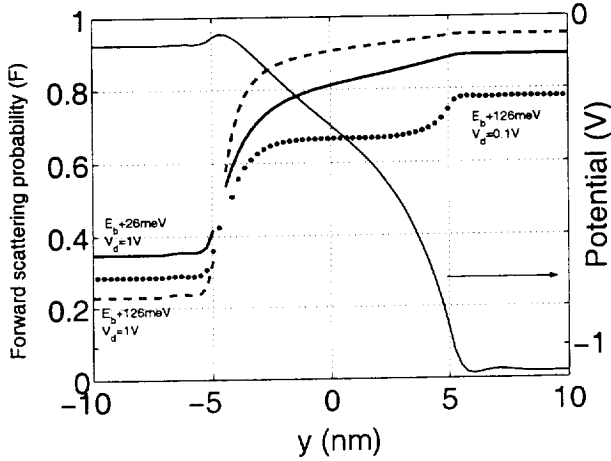


Fig. 2. Plot of the forward scattering probability (F) versus location of scattering between the source and drain. Note that scattering to the right of the source injection barrier does not cause as much reflection as to the left of the source injection barrier. Energy of the electron ($E_b + 26$ or 126 meV) and the drain voltage ($V_d = 0.1$ or 1 V) for the curves are specified. The main points are: (a) F is small to the left of the source injection barrier. (b) F increases with y to the right of the source injection barrier as the density of states below the source injection barrier aids current flow. (c) The higher energy electron is more ballistic to the left of the source injection barrier and less ballistic to the right of the source injection barrier. (d) Comparing the data for the two different drain voltages, we immediately see that F to the right of the source injection barrier is smaller for a smaller applied voltage. Experiments also show smaller ballisticity at smaller drain voltages.

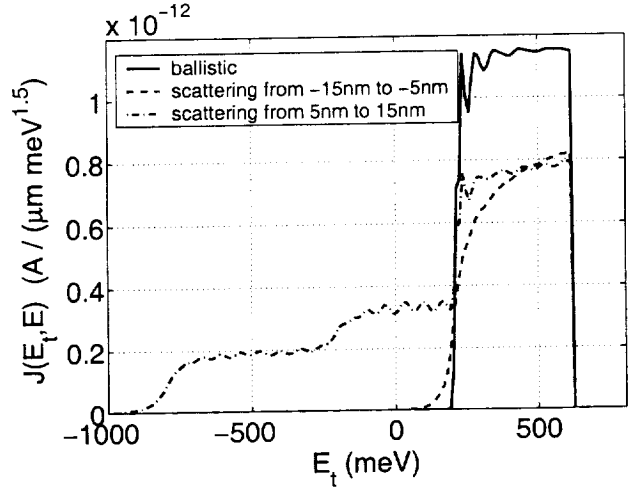


Fig. 3. Current distribution versus E_t (energy in the plane of the MOSFET in the inset of Fig. 1) at the drain end obtained by solving the transport equations with acoustic electron-phonon scattering for a case with a linear potential drop in the channel. Solid curve - ballistic, dashed / dash-dot - scattering is present only in Ex-s / Ex-d. Total energy (E) = 613 meV. The current at E is obtained by integrating the curves with the appropriate density of states. $l_{Ex-s} = l_{Ex-d} = l_{Ch} = 10$ nm. Scattering only in Ex-s results in a current distribution over an energy window that is very similar to the ballistic case, though, diminished in magnitude due to reflection (dashed). In contrast, scattering only in Ex-d has a large tail for E_t smaller than the conduction band at the source end (dash-dot). As a result of this tail, the influence of scattering in reducing the on-current is smaller due to scattering in Ex-d rather than in Ex-s. From this observation, it follows that Ex-s has to made smaller than the mean free path to increase ballisticity.

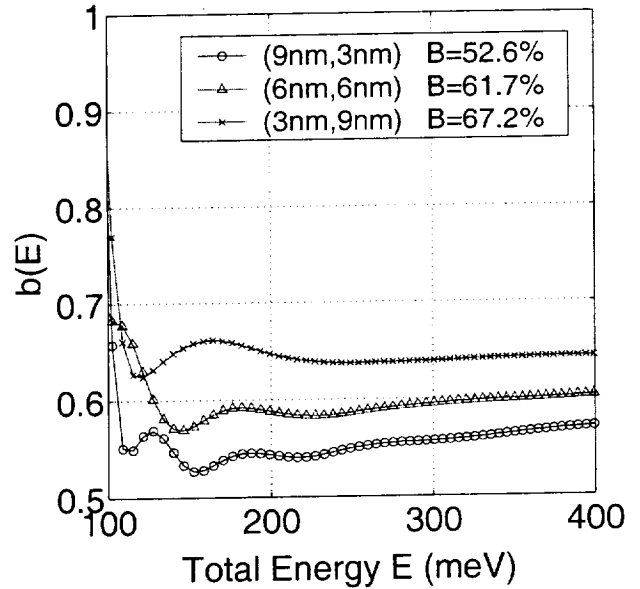


Fig. 4. Plot of ballisticity ($b(E)$) versus total energy. $l_{Ch} = 10$ nm, (l_{Ex-s}, l_{Ex-d}) are specified in the legend. Note that $l_{Ex-s} + l_{Ex-d} = 12$ nm. $b(E)$ is on an average larger at smaller energies.